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PERIPHERAL COUPLED TRAVELING WAVE ELECTRO-ABSORPTION MODULATOR

TECHNICAL FIELD

The invention is in the optoelectronic field. The invention is applicable to optical modulation systems.

BACKGROUND ART

Optical modulators are used in a variety of applications. Controlled modulation of light is useful in analog systems to produce an output proportional to the input signal. Digital optical systems, such as fiber optic communication systems, use optical modulators to impose digital signals on light. Digital optical modulators as signaling devices may also form the basis for optical memories and general computer devices.

One form of optical modulation is electro-absorption (hereinafter, "EA") modulation. In conventional EA modulation, EA material is an integral part of the optical waveguide. Consequently, the design of the microwave

waveguide is constrained by the optical waveguide design. It is necessary to trade off optical and microwave waveguide design considerations.

As a result, after considering various trade-offs, existing optimized EA modulators are typically 200 μm long or shorter, and the EA layer is a few thousand angstroms thick over the width of the waveguide. At such short interaction lengths, they do not take full advantage of traveling wave interactions. The size of the optical mode is approximately 1 to 2 μm, requiring expansive and precise coupling to single mode optical fibers. The high density of the optical field in the EA layer of an EA modulator of such a small mode also limits the saturation optical power of the modulator typically to a few milliwatts.

DISCLOSURE OF INVENTION

An embodiment of the present invention is directed to a method for optical modulation comprising the steps of guiding an optical wave in an optical waveguide, the optical wave having an evanescent tail; and applying a modulation voltage to the evanescent tail.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a schematic cross-sectional view of an embodiment of the invention; and

FIG. 2 is a schematic cross-sectional view of another embodiment of the invention.

BEST MODE OF CARRYING OUT THE INVENTION

Broadly stated, embodiments of the invention use peripheral coupling of a microwave wave and an optical wave. With the invention, strong EA modulation may be achieved. Embodiments of the invention may achieve

number of benefits, including separation of design optimization for optical waveguides and microwave waveguides working together to modulate an optical wave; provision of a millimeters-long synchronized length for interaction between a microwave wave and an optical wave obtaining a very low modulation voltage; microwave transmission line design with low attenuation and impedance matching to the source; relatively easy optical coupling to fibers; and large optical saturation power compared to other EA modulators.

Turning now to FIG. 1, showing a schematic cross-section of an embodiment of the invention, an apparatus for optical modulation includes an optical waveguide 10 and a microwave waveguide 12. Microwave waveguide 12 has an EA material 14 sized and placed such that, for an optical wave of interest guided in optical waveguide 10, EA material 14 is located in an evanescent region 16, a region occupied by the optical wave's evanescent tail when the optical wave of interest is being guided in optical waveguide 10.

Optical waveguide 10 includes substrate 18, an N-doped upper semiconducting cladding layer 20, a semiconducting core layer 22 disposed between substrate 18 and upper semiconducting cladding layer 20, and a lower semiconducting cladding layer 24 disposed between substrate 18 and semiconducting core layer 22. A heavily doped N-contact layer 26 is disposed on upper semiconducting cladding layer 20, and N-contact layer 26 and the upper part of upper semiconductor cladding layer 20 and are etched to form a ridge for optical waveguide 10.

Semiconducting core layer 22 has a higher index of refraction than that of lower semiconducting cladding layer 24 and of upper semiconducting cladding layer 20. This structure provides vertical confinement of an optical wave in optical waveguide 10. The ridge structure of N-contact layer 26 and the upper part of upper semiconducting cladding layer

20 provides lateral confinement of the optical wave in optical waveguide 10.

Optical waveguide 10 and microwave waveguide 12 share N-contact layer 26 within the ridge structure. Microwave waveguide 12 further includes two N-contacts 28, which are disposed on an upper surface of N-contact layer 26 at the outer edges of that upper surface.

Microwave waveguide 12 further includes an EA material 14 disposed on N-contact layer 26 between the two N-contacts 28, a P-contact layer 30 disposed on EA material 14, and a P-contact 32 disposed on P-contact layer 30. EA material 14 may be formed from a Group III-V compound material. One embodiment of the invention uses InGaAsP for EA material 14. Another embodiment of the invention uses GaInAlAs for EA material 14.

When guided in optical waveguide 10, an optical wave of interest is primarily in semiconductor core layer 22, but it also extends into lower semiconductor cladding layer 24, upper semiconductor cladding layer 20, N-contact layer 26, EA material 14, and beyond. Most of the optical intensity of an optical wave of interest when guide in optical waveguide 10 is located in a main mode that occupies main mode region 34, and the amplitude of the optical wave decays as it extends further away from semiconductor core layer 22. The part of the decaying optical wave in lower semiconducting cladding layer 24, the upper semiconducting cladding layer 20, N-contact layer 26, and EA material 14 is called the evanescent field, evanescent wave, or evanescent tail. The region in which the evanescent tail is present when an optical wave is being guided in optical waveguide 10 is shown as evanescent region 16. As the optical properties (i.e., the absorption coefficient and the refractive index) of EA material 14 are changed by the electric field produced by the modulation voltage applied to the microwave waveguide 12, the optical properties of EA material 14 in turn affect the propagation of the optical wave in optical waveguide 10 through the evanescent tail in evanescent region 16, enabling the

modulation of the optical wave by the microwave voltage. The coupling of EA material 14 in the microwave waveguide 12 to the modulation of the optical wave in the optical waveguide 10 via the evanescent field in evanescent region 16 constitutes the peripheral coupling of the microwave waveguide 12 and the optical waveguide 10.

FIG. 2 shows a schematic cross-sectional view of another embodiment of the invention. The structure of the substrate 18, lower semiconducting cladding layer 24, and semiconducting core layer 22 is the same as in FIG. 1. In this embodiment of the invention, upper semiconducting cladding layer 20 and N-contact layer 26 are etched differently to form a different contact structure and a different ridge structure for lateral confinement of the optical waveguide 10 mode. Two N-contacts 28 for the microwave waveguide 12 are disposed on N-contact layer 26, one on either side of main mode region 34 and evanescent region 16 of optical waveguide 10. N-contact layer 26 and upper semiconducting cladding layer 20 are etched away between each N-contact 28 and main mode region 34 and evanescent region 16 of optical waveguide 10 to form a ridge for lateral confinement of an optical wave in optical waveguide 10. Optimizations of embodiments of the invention will place the N-contacts 28 relatively far away from the ridge structure of upper semiconducting cladding layer 20 and N-contact layer 26. In one embodiment of the invention, the N-contacts 28 are disposed at each edge of the etched-away areas opposite the ridge formed by the etched-away areas.

On the ridge, N-contact layer 26 is shared by optical waveguide 10 and microwave waveguide 12 in this embodiment of the invention. Microwave waveguide 12 includes N-contacts 28 disposed on N-contact layer 26 as discussed above and a structure on the ridge of optical waveguide 10 that includes EA material 14 disposed on N-contact layer 26, P-contact layer 32 disposed on either side of a top surface of EA material 14, insulators 35 on

either side of EA material 14 and P-contact layer 32, and a truncated "V"-shaped P-contact 36 with the truncated tip of the "V" in contact with EA material 14, disposed between either side of P-contact layer 32 and between insulators 35. Insulators 35 may be made of polyimide, for example.

Use of truncated "V"-shaped P-contact 36 surrounded by insulators 35 reduces the capacitance of microwave waveguide 12. A relatively thick (referring to the vertical dimension in FIG. 2) truncated "V"-shaped P-contact 36 reduces microwave loss in microwave waveguide 12. The tip of truncated "V"-shaped P-contact 36 increases the electric field in EA material 14. An approximate 5.0×10^6 V/m strength is necessary for modulation. This may be achieved by all inventive embodiments. The FIG. 2 embodiment achieves high field strengths at especially low drive voltages. For example, at a drive voltage of 1 V, an electric field of 1.0×10^7 V/m may be achieved in parts of EA material 14. In an embodiment of the invention, the tip of truncated "V"-shaped P-contact 36 need be only 0.5 μm wide, but the width and position of the tip do not need to be maintained with a high degree of accuracy.

In an embodiment of the invention, EA material 14 is a multiple quantum well material. EA material 14 typically consists of several quantum wells. For instance, for 1550 nm wavelength modulation, EA material 14 may be a five-quantum-well stack each of which is made of an InGaAsP well (optimally 100 Å thick with a bandgap energy of 0.8 eV) and an InGaAsP barrier (optimally 70 Å thick with a bandgap energy of 1.08 eV). In another embodiment of the invention, EA material 14 is made of Franz-Keldysh effect materials, e.g., InGaAsP that is 1000 Å thick with a bandgap energy of 0.85 eV, optimized for 1550 wavelength modulation.

One of the benefits of embodiments of the invention is that those embodiments permit separation of design optimization for optical waveguide

10 and microwave waveguide 12 working together to modulate an optical wave. A discussion of certain design considerations permits description of preferred embodiments of the invention, using the exemplary embodiments illustrated in FIGS. 1 and 2 among several embodiments.

Let z be the direction of propagation of optical waveguide 10 and microwave waveguide 12. I_o is the incident optical power in optical waveguide 10 at the input (z=0) and I(z=L) is the transmitted optical power in optical waveguide 10 at the output end (z = L). The microwave wave field in EA material 14 is given by the microwave voltage at z, $V_{RF}(z)$, divided by $d_{i,eff}$, the effective thickness of EA material 14. For microwave waveguide 12 at low frequencies, $d_{i,\ eff}$ is approximately the physical thickness of EA material 14. At high frequencies, $d_{i,\ eff}$ may be larger than the physical thickness of EA material 14 and may be determined from microwave field analysis. The transmission function of any traveling-wave EA modulator (hereinafter, "TWEAM") in response to a continuous-wave microwave voltage $V_{RF}\cos\omega t$ at z=0 is:

$$I(z=L)/I_o(z=0)=T=\eta_{ins}\cdot e^{-\Gamma\alpha_{bias}L}\cdot e^{-\Gamma\Delta\alpha_{eff}(\Delta F)L} \qquad (1)$$

where

Γ = optical confinement factor of EA material 14;

η_{ins} = insertion efficiency = $C_{in}C_{out}$ $(1\text{-}R)^2$ $e^{-\alpha_o L}$;

$\Delta\alpha_{eff}L$ = integrated EA over L = $\int_0^L \Delta\alpha(\Delta F(z))dz$;

$\Delta F(z)$ = electric field seen by optical wavefront = $\dfrac{V_{RF}\cdot e^{-(\alpha_{rf}z/2)}}{di,eff}\cos(\omega t-\delta z)$;

δ = phase mismatch of microwave wave and optical wave = $(n_{mirowave}-n_{eff,opt})\omega/c$; and

α_{rf} = microwave propagation loss per unit length.

A modulation voltage ΔF will create a $\Delta\alpha_{eff}$ that will change transmission T. The optimization of the $\Delta\alpha$ (as that measured from the biasing voltage) by the ΔF is primarily a materials issue. In addition, modulation of T is affected by L, Γ, η_{ins}, α_{bias}, δ, α_{rf}, and $d_{i,eff}$.

When microwave waveguide 12 is perfectly impedance matched at its input and the output ends and when there is no microwave propagation loss, V_{RF} is just a constant (half of the microwave source voltage). When there are mismatches at the input and output end or attenuation, V_{RF} is a function of z that consists of attenuated forward and backward propagating waves. Described herein is the effect of microwave attenuation as it reduces the magnitude of V_{RF} as z increases from 0, without describing $V_{RF}(z)$ mathematically. The insertion efficiency η_{ins} consists of the coupling efficiency to the laser or the fiber at the input and the output ($C_{in}C_{out}$), the Fresnel reflections at the input and the output ($(1-R)^2$) and the optical wave residual propagation loss ($e^{-\alpha_o L}$, excluding the absorption due to the EA effect). $e^{-\Gamma\alpha_{bias}L}$ represents the reduction of the transmission T due to the EA effect of the bias voltage. At zero bias voltage, $e^{-\Gamma\alpha_{bias}L}=1$.

Equation (1) describes a modulation voltage that has a time variation of $\cos\omega t$. In that case, matching of $n_{microwave}$ and $n_{optical}$ (i.e., matching of the microwave and optical phase velocities or $\delta = 0$) will yield the largest $\Delta\alpha_{eff}$ for a given α_{rf} and $V_{RF}/d_{i,eff}$. For pulse modulation, Eqn. (1) will be modified. In that case, the matching of the optical and microwave group velocities will achieve the most effective modulation. Clearly, the most effective $\Delta\alpha_{eff}$ for a given drive voltage is obtained when there is the smallest $d_{i,eff}$, least microwave attenuation, best matching of phase and/or group microwave and optical velocities and best impedance matching of microwave waveguide 12 to the microwave driver. In addition, the smaller the Γ, the

smaller the density of the optical radiation in EA material 14, and the larger the saturation limit of the total optical power modulated by embodiments of the invention. The larger the optical mode, the smaller the propagation loss of optical waveguide 10 caused by scattering, and the more conveniently embodiments of the invention may be coupled efficiently to single mode optical fibers.

In digital applications, the bias voltage for the on-state is normally zero. Thus, $I_{on} = I_o T = I_o \eta_{ins}$ at the on-state. In an embodiment of the invention, $C_{in}C_{out}$ is maximized, R is minimized, α_{rf} is minimized, and α_o is minimized. The maximum L that can be used will depend on the insertion loss allowed, $C_{in}C_{out}$, R, and the residual propagation loss α_{rf} and α_o. At the off-state, the output power is I_{off} and

$$I_{off}/I_{on} = extinction \quad ratio = e^{-\Gamma\Delta\alpha_{eff}(\Delta F)L} \tag{2}$$

The most effective modulator would have the smallest V_{RF} that must be used to achieve a given required extinction ratio, requiring the most sensitive $\Delta\alpha(\Delta F)$ and the largest ΓL in optical waveguide 10, plus the smallest $d_{i,eff}$ in the microwave waveguide 12. To obtain large $\Delta\alpha_{eff}$ for a given $d_{i,eff}$ and a given $\Delta\alpha(\Delta F)$, the best group velocity matching, the least microwave attenuation, and the best matching to the driver circuit are required in microwave waveguide 12. Much better overall performance can be obtained by using small Γ and large L (L will be limited by α_{rf} and α_o) in embodiments of the invention. The Γ is kept as large as possible as long as the optical power is sufficient for the application, and the microwave/optical coupling configuration is sufficiently weak to achieve the microwave objectives (very small $d_{i,eff}$, low attenuation, plus velocity and impedance matching) without

affecting seriously the optical design that gives large η_{ins}, relatively easy coupling, and large L. Embodiments of the invention may place microwave waveguide 12 away from the center of a ridge structure of N-contact layer 26 and the upper part of upper semiconducting cladding layer 20 to reduce α_o. A result of embodiments of the invention is a large ΓL as well as a large $\Delta\alpha_{eff}$, using small drive voltage.

When the Franz-Keldysh effect is used for EA, $e^{-\Gamma\Delta\alpha_{eff}L}$ will be less sensitive to optical wavelength change. A Franz-Keldysh peripheral coupling TWEAM may be designed to achieve a minimum extinction ratio for a group of wavelengths in Wavelength Division Multiplexing ("WDM") applications. Since embodiments of the invention allow microwave waveguide 12 be placed on one side of optical waveguide 10, other optical structures such as a periodic structure may also be added to optical waveguide 10 from the top to achieve desired chirping effects. Novel structures for EA material 24 such as inner barrier step quantum well ("IQW") material may also be used to control chirping effects.

In analog applications, the modulation voltage is a small signal to the bias voltage. The criteria used to measure the link performance (with matched impedance at the input and the output) is the RF gain under a given bias condition,

$$G_{RF} = \left(I_o \cdot \eta_{ins} \cdot \partial T / \partial V \cdot \eta_{\det}\right)^2 \cdot R_{in} \cdot R_{out} \qquad (3)$$

where η_{det} is the detector efficiency, V is the input RF modulation voltage, and R_{in} and R_{out} are the source and load resistance at the detector. Under a given bias condition,

$$T = \eta_{ins} \cdot e^{-\Gamma \alpha_{bias} L} \cdot e^{-\Gamma L \Delta \alpha_{eff} (F_m \cos \omega t)}$$

$$\partial T / \partial V_m = -\frac{\Gamma L}{d_{i,eff}} \eta_{ins} \cdot e^{-\Gamma L \alpha_{bias}} \cdot \frac{\partial \Delta \alpha_{eff}}{\partial F_m} \Big|_{bias} \qquad (4)$$

Here the modulation field in EA material 24 is F_m, $F_m = V_m / d_{i,eff}$. V_m is produced by the RF drive voltage V. Dependent on the α_o and α_{bias}, there is a value of optimum L that maximizes $\partial T/\partial V_m$. In addition, α_{bias} and $\partial \Delta\alpha_{eff}/\partial F_m$ also vary as the bias voltage is varied. The best RF gain is obtained with the highest η_{ins}, the largest I_o, and the largest $\partial T/\partial V$. $\partial T/\partial V$ is maximized by the optimum ΓL and the smallest $d_{i,eff}$. Embodiments of the invention permit use of small Γ and large L to obtain the optimum ΓL. I_o, limited by saturation, can be increased by reducing Γ. High η_{ins} with relatively easy coupling is obtained by using a large optical mode. An optimal design of microwave waveguide 12 should yield the smallest $d_{i,eff}$ and the largest $\partial \Delta\alpha_{eff}/\partial F_m$. Since $\partial T/\partial V_m$ contains $e^{-\alpha_o l}$, the design of optical waveguide 6 should have $\alpha_o L << \alpha_{bias}\Gamma L$. When $\alpha_o L << \alpha_{bias}\Gamma L$, the maximum $\partial T/\partial V_m$ occurs approximately at $e^{-bias\Gamma L} = 0.5$. At this optimum ΓL the maximum $\partial T/\partial V_m$ depends only on $d_{i,eff}$, α_{bias} and $\partial \Delta\alpha_{eff}/\partial F_m$. Besides RF gain, the other important consideration in analog applications is the reduction of non-linear distortion. A number of techniques for reduction of non-linear distortion may be realized in embodiments of the invention.

Since embodiments of the invention allow high η_{ins} and large $\partial T/\partial V$, $G_{RF} > 1$ may be obtained at large I_o. In that case, wide bandwidth RF amplification may be achieved that cannot be obtained electronically. In principle, such a RF amplifier may be integrated on the same chip. As with embodiments of the invention for digital applications, embodiments of the invention using the Franz-Keldysh effect may be used for various adjacent

wavelengths with the RF gain controlled by adjustment of bias voltage.

While various embodiments of the present invention have been shown and described, it should be understood that modifications, substitutions, and alternatives are apparent to one of ordinary skill in the art. Such modifications, substitutions, and alternatives can be made without departing from the spirit and scope of the invention, which should be determined from the appended claims.

Various features of the invention are set forth in the appended claims.